

UNCLASSIFIED

Defense Technical Information Center
Compilation Part Notice

ADP011771

TITLE: Development of a mm-Wave Imaging System for the W7-AS
Fusion Experiment

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: International Conference on Terahertz Electronics [8th], Held in
Darmstadt, Germany on 28-29 September 2000

To order the complete compilation report, use: ADA398789

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:

ADP011730 thru ADP011799

UNCLASSIFIED

Development of a mm-wave imaging system for the W7-AS fusion experiment

Stefan Bäuml, Georg Michel, Manuel Rodriguez-Gironés, Hans L. Hartnagel, Hans-Jürgen Hartfuß

Abstract – The intensity of the electron cyclotron emission (ECE) along a radial sightline of a magnetically confined fusion plasma can be used as a measure for the local temperature of the plasma electrons. The electron temperature is not constant in time but shows fast fluctuations with relative amplitudes of the order of less than 1% with a frequency spectrum extending into the MHz range of frequency. To get deeper insight in the physics of this plasma turbulence two-dimensional information about the fluctuating structures is indispensable. For the two-dimensional spatio-temporal characterization of these temperature fluctuations in the core of the W7-AS plasma an ECE imaging system is being developed.

As a first step an array of four vertically staggered sightlines is being built up with eight radial channels along each sightline. A mm-wave detector array acting as the front end of a multichannel heterodyne radiometer system consists of four channels of which each is made up of an antenna, a mixer, filters and the on-chip local oscillator power distribution for the individual mixers. This high frequency part is being developed in collaboration with TU Darmstadt. An alternative approach has already been installed using four conventional, separated mm-wave mixers allowing for first experiments.

I. INTRODUCTION

Electron cyclotron emission from a magnetically confined plasma is a direct consequence of the gyration motion of the electrons around the lines of the magnetic field. It occurs at the gyration frequency $\omega = n \cdot \frac{eB}{\gamma \cdot m_e}$

and its harmonics ($n=1,2,3,\dots$). ω is called the electron cyclotron frequency; e and m_e are the electron charge and mass, respectively, B is the magnetic induction and γ the relativistic factor with $\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$. Radiometry of

electron cyclotron emission is used on many fusion devices as a standard diagnostic for radial profiles of the electron temperature by the spectral measurement of $I(\omega)$, the absolute mm-wave intensity¹. In a toroidal plasma configuration like a stellarator or a tokamak $B(R)$ along a radial sightline is monotonically varying, so that the spectral information of the ECE measurement transfers into spatial information.

If the fusion plasma is optically thick for all frequencies resonant inside the plasma torus, i.e. all radiation is absorbed by the electron resonance in a single pass of the

wave through the plasma, the plasma absorbs and by Kirchhoff's law also emits radiation I_{BB} as a blackbody radiator. In this case the radiation intensity depends only on the electron temperature. The blackbody intensity I_{BB} radiated power per unit area and unit solid angle is given

by Planck's law, $I_{BB}d\omega = \frac{\hbar\omega^3}{8\pi^3c^3} \frac{1}{e^{(\hbar\omega/kT)-1}} d\omega$, where

$d\omega$ denotes the observed frequency interval. For present day fusion plasmas $\hbar\nu < 1\text{meV}$, $kT > 10\text{eV}$, so that $\hbar\nu \ll kT$ and the Rayleigh-Jeans approximation holds:

$$I_{BB}d\omega = \frac{\omega^2}{4\pi^2c^3} kT. \text{ Here } k \text{ denotes the Boltzmann}$$

constant and c the speed of light in vacuum. So, if the electron velocity distribution perpendicular to the magnetic field has a Maxwellian distribution one can identify the apparent radiation temperature T with the temperature of the gyrating electrons $T=T_e$. Therefore spectrally resolved ECE measurements along one single radial sightline yield a radial profile of T_e .

It is the goal of ECE imaging systems to map several of these radial sightlines onto a two-dimensional ($m \times n$) array of detector elements in order to get a three-dimensional image of the plasma properties measured by the ECE diagnostic. By using filterbanks in the radiometric system of the ECE diagnostic T_e can be measured simultaneously in each of the planes at different radial positions, that correspond to different center frequencies of the filters in one filterbank and results in the third dimension of the image. The situation is illustrated in Fig. 1 for a $m \times n$ element array with eight filters in each filterbank.

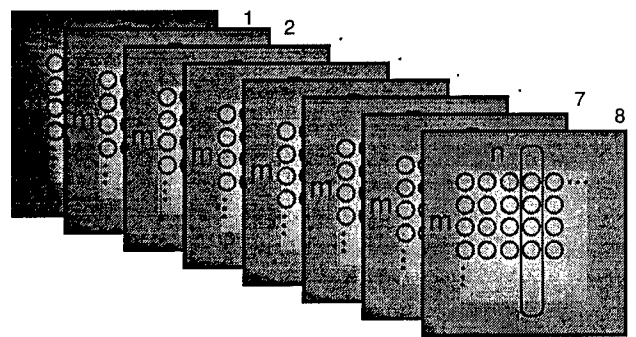


Fig. 1: Sketch of the mapping of $m \times n$ radial sightlines coming from an array of $m \times n$ detectors. The blue box marks a four element array as planned for W7-AS.

II. ELECTRON TEMPERATURE FLUCTUATIONS MEASURED BY ECE

In order to use an ECE-diagnostic as described above for measurements of the T_e fluctuations, some important preconditions concerning temporal and spatial resolution

S. Bäuml, G. Michel and H.-J. Hartfuß are with the Max-Planck-Institut für Plasmaphysik, EURATOM Ass., Wendelsteinstr. 1, 17491 Greifswald

M. Rodriguez-Gironés and H. L. Hartnagel are with the Institut für Hochfrequenztechnik, Merckstr. 25, 64283 Darmstadt

have to be fulfilled. The temporal resolution of a radiometric system is determined by the post-detection filter bandwidth B_V and can be made easily as high as a few MHz. The radial resolution is determined by the predetection bandwidth B_{IF} , which is about 300 MHz. The optical depth together with the relativistic broadening define a kind of natural lower limit for the radial resolution, which is about 0.5-1cm for typical fusion plasmas. The poloidal resolution is diffraction limited and determined by the type of optical arrangement used. Minimum reported values are 1-2 cm. Unwanted finite sample volume effects lead to increased phase velocities derived and restrict the wave number range of the fluctuation diagnostic.

The inherent intensity fluctuations of a thermal radiation source is denoted by $i(t)$ and is called wave or thermal noise. The ratio $i(t)/I_{BB}(t)$ in radiometry at high radiation temperatures is governed exclusively by these inherent intensity fluctuations superimposed to the mean intensity $I_{BB}(t)$ of the blackbody radiation of the plasma. It is determined by the radiometers bandwidth ratio of post- and pre-detection bandwidths:

$$\frac{\sqrt{\langle i(t)^2 \rangle}}{\langle I_{BB}(t) \rangle} = \sqrt{\frac{2B_V}{B_{IF}}},$$

which is about 5% for a typical ECE radiometer. This is the minimum level possible for a single mode heterodyne radiometer. This phenomenon sets a severe limit to fluctuation measurements burying completely "true" temperature fluctuations below a relative level of 5%. This problem can be overcome by applying correlation techniques and making use of the coherence properties of the thermal radiation. In the past the existence of these T_e fluctuations was proven² and further investigations concerning their correlation with density fluctuations were made³.

III. SYSTEM SPECIFICATIONS

In a first step it is planned to build an antenna array consisting of four separated conventional antennas and harmonic mixers. In a second step a MMIC (monolithic microwave integrated circuit) mixer array with integrated antennas is being developed. The intermediate frequency (IF) parts of both systems are made up by filter banks which can be used for both of the systems.

To be able to do measurements at different radial positions along a single sightline simultaneously, a wideband single sideband detection scheme with fixed LO signal is chosen. The local oscillator (LO) frequency is 133 GHz for harmonic mixing and 67.5 GHz for subharmonic mixing using the MMIC array. The bandwidth of the working frequencies (RF) of both systems is about 10 GHz and centered around 146 GHz (2nd harmonic ECE), corresponding to the high field side of the electron temperature profile for 2.5 T.

The IF part consists of eight radial channels for each of the poloidally staggered antennas, which results in 32 radial channels for the ECE imaging systems. The intermediate frequency is chosen below 18 GHz to avoid additional complication with the detector array under development.

The first IF stage uses an amplifier with low noise figure (1.3 dB). After further IF amplification and signal splitting, the total signal bandwidth is reduced to 300 MHz by the eight bandpass filters which comprise the filterbank. Each center frequency of a filter marks a different radial position along the sightline of the corresponding poloidal antenna in the plasma. The bandwidth together with the center frequency of each filter determine the radial section along the chord. Finally the signals are detected with Schottky diode detectors and the output voltage of each video-channel is applied to the data acquisition.

IV. ECEI USING CONVENTIONAL IMAGING TECHNIQUES

A system of four identical radiometers comprises the ECEI approach using conventional focal plane imaging techniques. For the measurement of the 2nd harmonic ECE at about 146 GHz a Gaussian beam is formed by an elliptical mirror and a corrugated circular feed horn. The mirrors and the horns are placed inside the vacuum vessel. Fig. 2 shows the setup of the system inside the stellarator W7-AS.

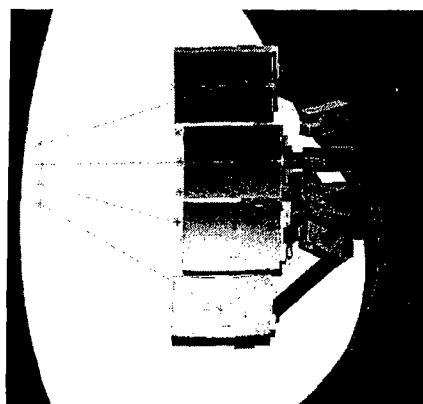


Fig. 2: CAD sketch of the four mirror-array showing the four elliptical mirrors together with the corrugated millimeter-wave horns inside the plasma vessel.

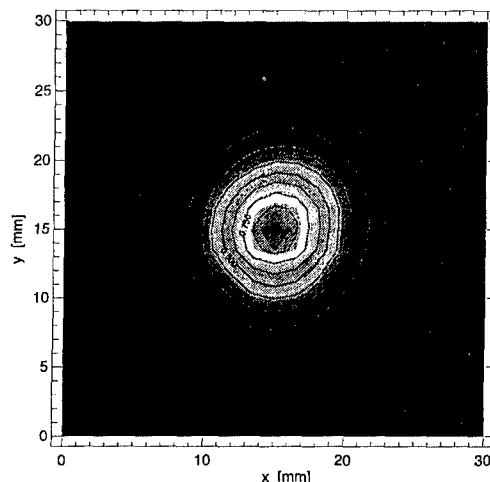


Fig. 3: Measurement of an antenna pattern. Plotted is the antenna pattern near the focal plane of the elliptical mirror of one of the four identical optical arrangements.

The beam waist, located near the center of plasma is about 5 mm. Fig.3 shows a normalized contour plot of the measurement of an intensity pattern at the beam waist of the optical system. The system shows no detectable sidelobes. The signal coming from the plasma is transmitted by the mirror, the horn and a fundamental waveguide outside the vessel towards the single sideband receiver system. After bandpass filtering and downconversion of the signal to frequencies below 18 GHz it gets processed at the following IF-part of the system described before.

In Fig. 4 the center-frequencies of each of the four sightlines inside the plasma together with the shape of the Gaussian beams, indicated by the errorbars, are shown.

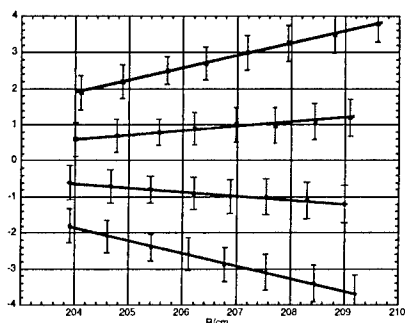


Fig. 4: Diagram of the calculated filter locations. Each of the datapoints along a sightline represents the place of the center frequency in real space (R, z). The vertical error bars indicate the beamwidths in z -direction.

The positions of the filters are chosen in a way, that the filters arranged one upon another are placed on the same magnetic flux surface. All filter positions are inside the so called Rayleigh lengths of the Gaussian beam, which is necessary for focal plane imaging systems.

Electron temperature fluctuations, their motion as well as their size inside the 50mm x 80mm detection volume will be revealed by using correlation techniques for neighbouring channels⁴. The system will also allow for investigations of coherent large scale fluctuations, so called MHD phenomena.

V. ECE IMAGING USING A MMIC ARRAY

The preceding section, especially Fig. 2, make clear, that for measurements of T_e fluctuations along a greater number of sightlines, which for example cover the whole plasma cross section, the spatial requirements of the optical arrangement at a fusion device are difficult to be fulfilled. Thanks to the miniaturization of the antenna and the mixer structures during the last decades it is possible to build small arrays made up of a number of these elements and allowing to map several sightlines on these arrays so that this problem can be overcome.

The development of two-dimensional detector arrays represents one of the main concerns of plasma diagnostics for 2D ECE imaging and also for applications in reflectometry and interferometry at fusion devices like TEXT-U⁵, GAMMA10^{6,7}, RTP⁸ and TEXTOR⁹.

Here a short description of the system under development for the stellarator W7-AS¹⁰ is given. The design of the fully MMIC 150 GHz subharmonic mixer array to be used for ECE imaging at W7-AS is discussed in detail on poster P.1 at this conference.

In a first step the system is planned to be made up of a four element array. Fig. 5 shows the layout of the four element receiver array. The four parallel subharmonic Schottky-diode mixers are realised on a microstrip line on a 70- μ m thick GaAs substrate. Rectangular patch antennas serve as RF receiving elements.

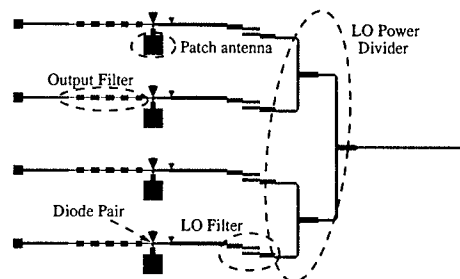


Fig. 5: Principal setup of two antennas mounted on a mixerblock. The RF signal from the plasma reaches the patch antennas. The LO signal is distributed on board. On the left hand side the IF stage follows.

As opposed to the receiver arrays on fusion devices mentioned above, which make use of quasi-optical techniques for the LO distribution^{5,6,7,8,9}, the circuit manufactured at the Technical University of Darmstadt distributes the local oscillator power directly on the chip.

The LO power gets fed to a 50 Ω microstrip line, thereby reducing significantly pumping power level requirements. The microstrip line acts as an LO filter and presents to the diodes a short circuit at IF and RF. Another structure on the other side acts as output filter. The RF antenna is also coupled to this structure. Cross-talk between channels is reduced by physical substrate separation to prevent propagation of substrate modes. To increase channel isolation further, the patch antennas can also be isolated. The circuit is designed to have 9 GHz RF- and IF-bandwidths. The diode pair has an anti-parallel structure, a configuration with well-known advantages^{11,12}. By reducing the pumping frequency to about 70 GHz, filtering is simplified, since the need to match an LO signal lying between RF and image bands is eliminated. This integrated circuit will be placed on the so called mixer. A backshort in the LO waveguide allows to carry out an optimisation of LO power distribution to the microstrip lines.

Simulations of the MMIC by using the method of moments predict excellent electrical attributes. The calculated conversion loss versus the output frequency for different values of pumping power available per channel indicates, that e.g. for a LO power of 8 dBm the conversion loss varies between 6 dB and 10 dB. Typical values of isolation between ports were also estimated. The LO-IF isolation is 31 dB. The LO power flowing towards the RF antenna is 41 dB below the injected LO level. The RF-IF isolation is 50 dB. Undesired down converted image signal at the IF port is between 10 and 30 dB below the desired IF frequency. This is due to the antenna acting as an image filter and to additional intended mismatching.

The optics for the MMIC ECEI system will be made up of a substrate lens and an additional elliptical mirror. Since only a circular vacuum port is available for the ECE imaging diagnostic at W7-AS, which is about 115

cm away from the plasma center, with only 10 cm in diameter, beam truncation would be the main problem for this diagnostic at W7-AS. The combination of these two concerns would make a refocussing of the beam necessary, but is prohibited by the limited space at this part of the vacuum vessel. It is planned to place the array in an immersion flange (see Fig. 6).

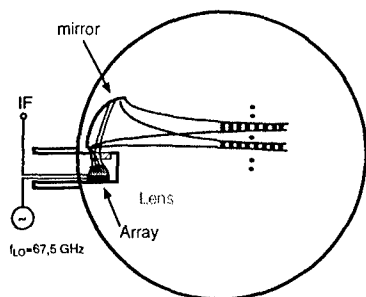


Fig. 6: Sketch of the planned W7-AS ECEI setup using a MMIC array placed in an immersion flange.

By a single focussing elliptical mirror inside the vessel, the radiation of the plasma will be focused onto the array, which is placed at atmospheric pressure together with another focussing lens. To ensure that the proper polarization is chosen, a polarizing grid is introduced into the sightline. LO power will be transmitted to the array by an oversized waveguide. The IF signal at the output of the array gets submitted to the IF section of the radiometer by coaxial cables.

Physical optics calculations were already performed in order to determine the expected E-field distribution coming from the rectangular patch antennas. Fig. 7 shows a contour plot of the amplitude of the electric field in front of the lens, which ends at $z=0$. Two of the sightlines are plotted.

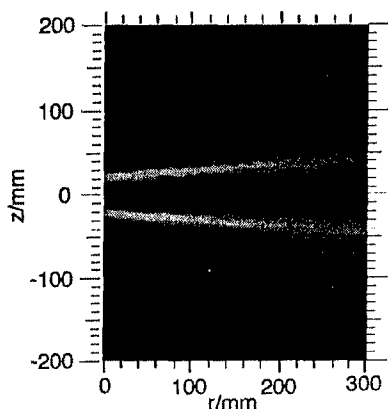


Fig. 7: Calculated sightlines of a two element array. Plotted is the E-field propagation along the radial sightline for two patch antennas in front of the lens, which is attached to the antennas.

The amplitude of the electric field in a plane perpendicular to the direction of propagation (z -direction) 10 cm away from the lens is plotted in Fig. 8. A separation of the two channels can clearly be identified. Simulations without using a substrate lens showed that the two sightlines cannot be separated any more.

But nevertheless, these encouraging simulations have to be verified by measurements. Especially the existence of sidelobes has to be tested in order to be able to use the

system for electron temperature fluctuation measurements.

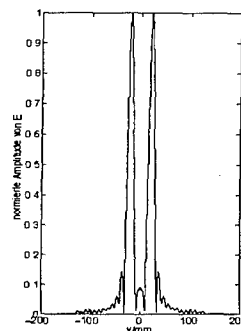


Fig. 8: Plot of the expected E-field distribution in z -direction 10 cm apart from the substrate lens of Fig. 7.

Acknowledgements

The authors would like to thank J.P. Pascual, M.L. de la Fuente and F. Lopez for their support at the MMIC array development. Acknowledgements also go to M. Bergbauer, M. Steffen and S. Radau for their assistance during the construction phase of the mixer block and their technical support for the setup of the conventional ECEI system.

References

1. H.J. Hartfuß, T. Geist, M. Hirsch, Plasma Phys. Control. Fusion, 39, 1693-1769 (1997)
2. S. Sattler, H.J. Hartfuß, W7-AS Team, Phys. Rev. Lett., 72, 653-656 (1994)
3. M. Häse, M. Hirsch, H.J. Hartfuß, Rev. Sci. Instrum., 70(1), 1014-1017 (1999)
4. B.H. Deng, D.L. Brower, G. Cima, C.W. Domier, N.C. Luhmann, Jr., C. Watts, Phys. Plasmas, 5, (12), 4117-4120 (1998)
5. R.P. Hsia, B.H. Deng, W.R. Geck, C. Liang, C.W. Domier, N.C. Luhmann, Jr., D. L. Brower, G. Cima, Rev. Sci. Instrum. 68(1), 488-491 (1997)
6. N. Oyama, A. Mase, H. Negishi, T. Tokuzawa, A. Itakura, T. Tamano, K. Yatsu, K. Watabe, K. Mizuno, Y. Nagayama, K. Kawahata, H. Matsuura, K. Uchida, A. Miura, Rev. Sci. Instrum. 70(1), 1003-1006 (1999)
7. N. Oyama, A. Mase, T. Tokuzawa, K. Imamura, A. Itakura, Y. Ito, T. Tamano, Y. Harada, K. Mizuno, Fus. Engineer. Design 34-35, 407-410 (1997)
8. B.H. Deng, R.P. Hsia, C.W. Domier, S.R. Burns, T.R. Hillyer, N.C. Luhmann, Jr, T. Oyevaar, A.J.H. Donne, and the RTP team, Rev. Sci. Instrum. 70(1), 998-1001 (1999)
9. C.W. Domier, B.H. Deng, A.J.H. Donne, P.L. Hsu, N.C. Luhmann, Jr., E. Mazzucato, H.K. Park, M.J. van de Pol, J. Wang, AP 20 at the 13th Topical Conference on High Temperature Plasma Diagnostics in Tucson, Arizona, 18-22 June 2000
10. S. Bäuml, M. Rodriguez, H.J. Hartfuß, ECE Imaging development at W7-AS, Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, paper P4.055, 1999
11. M. Cohn, J.E. Degenford, B.A. Newman, IEEE trans. on MTT, 23, 667-673 (1975)
12. C.-I. Lin, et al, "Anti-Parallel Planar Schottky Diodes for subharmonically pumped 220 GHz mixer", 10th Int. Symp. On Space Terahertz Technology, Charlottesville, Virginia, 16-18 March 1999